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Modelling Externalities between Ecological and Economic Systems

A Synthesis

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Keywords: economic-ecological interaction, spatial externality

Abstract

Environmental sustainability issues have in recent years received much attention from the side of environmental scientists and economists. There is a broad recognition on the relevance of external effects in open and interacting spatial systems. It would be helpful if ecological economic research would deploy an integrated analytical framework for investigation the complex nature of such multi-disciplinary issues. This paper aims to present a basis for a methodological synthesis for analysing environmental issues in open economic systems. It seeks to develop an integrative framework through which a great many ecological-economic studies can be mapped out and represented. The focus is the conceptual issues centring around the integration of interacting economic and ecological subsystems, *inter alia* in relation to spatial externalities and ecological footprints. The discussion enables us to build a framework for a systematic categorisation of various types of models for economic-ecological interaction. The paper concludes with some reflections on the way forward.

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1. Introduction

Spatial environmental issues have generated increasing interest among environmental policy-making institutions. One of the examples is the United Nations Framework Convention on Climate Change and the corresponding Kyoto Protocol. From a scientific point of view, the study of transboundary environmental issues is particularly interesting because of its multidisciplinary character. A proper methodological framework may lead to a better understanding of, and more synergy between, various environmental disciplines, which might result in significant scientific benefits from an interdisciplinary perspective. A drawback of multidisciplinarity is, however, that some of the integrated perspectives may be disputed on specific monodisciplinary grounds. This may contradict the principle of 'consilience', recently introduced by Wilson (1998), meaning that the methods and starting points of one scientific discipline need to be consistent with the accepted insights of other disciplines (see Van den Bergh 2000). Lack of consistency in ecological economics may lead to failure in explaining and offering possibilities for correcting severe and sometimes irreversible environmental degradation (for a review, see e.g. Van den Bergh 1996, 2000 and Spash 1999). This unfortunate situation has increasingly been recognized after the publications of the Report of the Club of Rome (Meadows et al. 1972) and the subsequent increasing political popularity of the concept of sustainable development (Brundtland 1987, Van den Bergh 1991, Pezzy 1992, Beder 1993, Toman et al. 1993, Goodland 1995, Faucheux et al 1996). It became gradually clear that the ecological system should be recognised as an integral entity - next to the economic system - in analysing environmental scarcity problems.

This paper aims to offer a methodological synthesis for various environmental models in terms of a unifying framework. Furthermore, we will illustrate this framework by presenting and discussing an integrative spatial-economic model with environmental interactions for economic activities, markets and externalities, followed by a discussion of ecological footprint issues in terms of transboundary externalities.

The plan of this paper is as follows. Section 2 first discusses the conceptual basis for analysing environmental externalities. Next, Section 3 presents a unifying modelling framework for the interaction between relevant economic and ecological systems. Section 4 then reviews and interprets various existing models in terms of the above-mentioned unifying framework, while Section 5 emphasizes the importance of spatial externalities as reflected e.g. in the ecological footprints. Finally, Section 6 offers some concluding research remarks.

2. Environmental Externalities

In this section we will concisely discuss the 'externality' and 'public goods' character of environmental amenities (Baumol and Oates 1975). In economic analysis, an externality is generally conceived of as a divergence between the marginal social and private cost of a good. Environmental damage thus typically involves a negative externality, when it is not (or not optimally) priced. The result is that a tax, subsidy or other governmental measure is justified in order to correct the impact of such an externality (Verhoef et al. 1997, Verhoef 1999, Verhoef and Nijkamp 2000). This description of an externality implies thus that (i) an externality exists when some agents' action influences the utility of other agents, without this effect being reflected in price signals (see e.g. Mishan 1971), and (ii) necessary conditions for a socially optimal situation (i.e., the Pareto-optimality conditions) are violated (Buchanan and Stubblebine 1962, Baumol and Oates 1975, Mas-Colell et al. 1995).

Although the concept of externality is widely used, various definitions still exist (Viner 1930, Mishan 1971, Meade 1973, Baumol and Oates 1975, Ng 1988), while some of them may be imprecise (as observed by Mas-Colell et al. 1995). This may be one reason why the concept of externality is not always clear to a non-economist (Sterner and Van den Bergh 1998). A fallacious loose interpretation would be that the ecological system can be considered as external to an economic system and 'therefore' irrelevant for economic efficiency (see for a review e.g. Van den Bergh 1996, Sterner and Van den Bergh 1998). This interpretation of externality is obviously missing the point, since the use of the externality concept implies, on the contrary, that the ecological system *does* matter to economic efficiency.

From an ecological perspective, it is often argued that economic growth may result in an increased use of natural resources and an increased damage to ecosystems as a result of pollution, even when externalities are optimised (Meadows et al. 1972; Daly 1990, 1997c). It is noteworthy that sustainable growth from a purely economic perspective (Solow 1974 and Hartwick 1977) may even have an interpretation that is different from the concept of 'sustainable development' based on an ecologically-oriented perspective (Holling 1973, Common and Perrings 1997). Thus, even when increasing scarcity of an environmental good would be coped with by an increase in environmental taxes – or, more broadly, in taxes that would in addition reflect intergenerational equity considerations (Withagen 1995, 1996) –, the outcome may still not be regarded as strictly sustainable (over an infinitely long time frame). This conclusion derives from the assumption that the earth is a closed system, as well as from the laws of thermodynamics (Ehrlich et al. 1993, Georgescu-Roegen 1993). These laws play important roles in the ecological perspective (Van den Bergh 2000).

In a similar vein, in terms of materials use the concept of 'material balance' has been put forward by ecological economists (Kneese et al. 1970, Ayres 1978, 1999, Ruth 1993, Van den Bergh 1996). Other researchers have resorted to the energy base as an integrating mechanism between economy and ecology (see e.g. Odum 1971), while also input-output studies have been advocated as a methodological framework for analysing economic-ecological interactions (see e.g. Isard 1972). A review of various early attempts is contained in Nijkamp (1977).

From an ecological perspective, various questions have been raised on the value basis of economics (see, for instance, the special issue on this topic in Ecological Economics of April 1998; Daly 1991, 1998; and Ayres 1998), as the main message seems to be to get the prices right. Others have argued that according to Georgescu-Roegen's application (1971) of thermodynamic laws to economics, it should be the physical quantities rather than economic values that should play a central role in studying sustainable development (e.g. Rees 1999, Wackernagel 1999a and Yount 1999). After all, the natural environment is limited in a physical -and not in a value- sense (Daly 1995, 1997a, b, Ayres 1998). Clearly, the ultimate goal of the 'homo economicus' is a quantity-oriented one – that is, the maximisation of welfare as enjoyed from the consumption of scarce material goods, be it ordinary market goods or improperly priced natural goods (see e.g. Mas-Colell et al. 1995, Samuelson 1947). Economic theory, ever since Adam Smith, has shown that the transactions of utility maximising economic subjects tend to result in a competitive market equilibrium that is Pareto-optimal (the 'First Theorem of Welfare Economics'). Efficient prices are not the ultimate goal, but only instruments.

Of course, this theorem holds true only under the usual assumptions of absence of market failures. In case of imperfections and non-optimal outcomes in environmental goods resulting e.g. from the existence of externalities, due attention should be paid to the interaction between the economic and the ecological system, especially if the interactions between and within both systems are complex and non-linear. Economists have argued that an efficient solution can be achieved by using a system of taxes (e.g. Pigouvian taxes) that is consistent with the size of the externalities. Clearly, a practical pricing of all attributes or elements of an ecological system might hardly be possible, but in that case we may resort to the theory of 'second-best' environmental taxation. There is a large and growing body of literature on this issue, emphasising the economic aspects of relaxing various simplifying traditional assumptions on environmental spillovers (see *e.g.* Verhoef and Nijkamp 1999).

3 Integrated economic-ecological systems

In this section, we will present a framework for modelling the interaction between ecological and economic systems, which serves as the basis for encapsulating a number of approaches in the literature aimed at studying the relations between the economy and the ecology. As will be shown, the result of this framework may also be associated with relevant complementary approaches such as the material balance model (see e.g. Van den Bergh 1991, 1996; Van den Bergh and Nijkamp 1994). In the framework proposed here, we will follow Bossel (1986), who used the term system as a means "*to describe a set of components interacting relatively strongly with each other and relatively weakly with their common environment, in a way which allows one to recognize a 'purpose' in the resulting overall behavior of the interacting components*" (p. 51). In the context of our paper, the following four starting points are taken for granted: (i) the social objective in general is an increase in the 'quality of life' at all relevant points in time, and may take various forms (for instance, a maximization of the discounted net present value of the quality of life); (ii) a system is composed of well-defined elements or constituents which focus on the most essential features of the system; (iii) a system has a formal structure that maps out the interaction between the elements; and (iv) a system has a boundary which separates it from the external environment (in our case, we study only the integration of an economic and ecological system).

In Figure 1, the general conceptual framework of an integrated economic-ecological (henceforth: E-E) system is presented. For notational purposes, in this and the subsequent figures, we use circles to denote variables (input or output) and rectangles to denote transformation processes; the straight and elbow connectors denote relationships between two elements in a pure economic system and the curved connectors denote relationships between two elements that may be extended from the standard simple economic model. The curved connectors imply the possible existence of an externality in case the economic system attaches a zero (or a very low) price to these elements in case of a competitive market, while in a Pareto-optimal case these elements would have the corresponding efficient value. Table 1 summarises the notation used.

Symbol	Description	Function	Description
K	Physical capital	A(•)	Knowledge accumulation function
L	Labour	δ(•)	Depreciation function
I	Investments in capital	F(•)	Production function
C	Consumption	E(•)	Emission function
S	Stock of ecological resources	R(S)	Regenerative function of the ecological system
		U(•)	Utility function

Table 1: Notation used in the framework model

This conceptual model is exteremely rich in scope and is able to act as an 'envelope' model for many existing environmental-economic models, as will be shown in Section 4. We will first give some explanation on this synthesis framework. In this integrated system, we have input factors such as physical capital (K), labour (L) and the stock of ecological resources (S). The latter factor may refer to both an ecological 'good' (e.g. fish), in which case the flow E represents 'extraction', and a 'bad' (e.g. accumulated CO_2), in which case E stands for 'emissions'. It is of course not inconceivable that a stock that is a 'good' in one range (for instance nearly extinguished rabbits) becomes a 'bad' in another range (for example an over-population of rabbits).

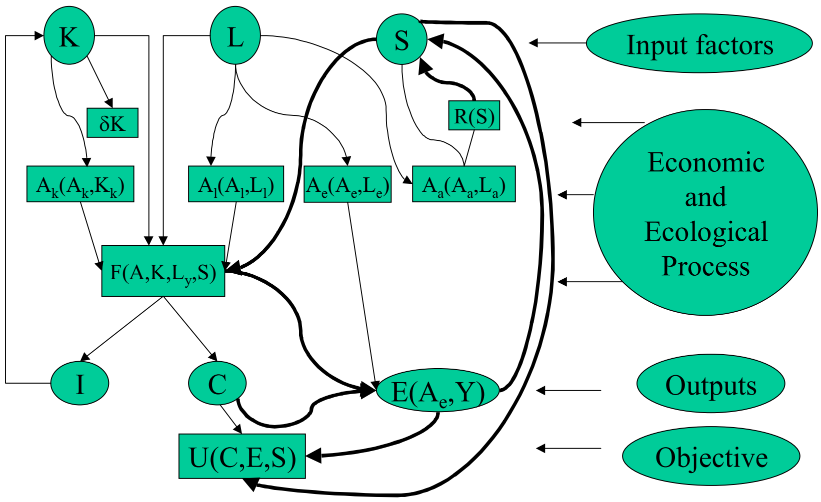

Figure 1: A general conceptual model of an integrated economic and ecological system

Input factors are transformed into the output factors through the economic and ecological process. Firstly, the ecological process is abstracted as the regenerative capacity of the ecological system and is symbolised as R(S). Secondly, the economic process consists of the production process (F(K,L,A,E,S)) of the physical output as well as technological development (A). Essentially, we could distinguish four forms of technological developments: basic knowledge (A_k), human capital knowledge (A_l), knowledge on efficient emission technology (A_e) and knowledge on efficient abatement technology (A_a). The developments of these knowledge systems depend on the existing knowledge level as well as on extra input in the form of capital and/or labour (in which case endogenous growth theory comes into play). Finally, we have to face also the depreciation of physical capital (δ_k) that could be the result of either economic or ecological processes. We note that the figure ignores the possibility of depreciation of knowledge.

The input factors are, via the economic and ecological process, transformed into outputs. The outputs consist of (i) investments, (ii) consumption and (iii) emission. Emission as well as investments have a feedback function. Consumption is one of the main elements in the valuation process from an economic perspective. The social objective in this integrated system is formed by the utility from consumption (positive), emission (negative) or extraction, and the value of the ecosystem (with either positive or negative changes depending on whether it is an improvement or deterioration). Clearly, this framework might be extended with time-dimensions (see e.g. Braat and Van Lierop 1987) in order to include turnover time, linear and non-linear dynamics and a time horizon. Similarly, different spatial scales can be introduced, such as areal information, interregional interaction patterns or ecological footprint (see Wackernagel 1999b).

Then, in order to derive analytical or numerical results, the functional form for the system's structure should be chosen and a quantification of the parameters should be given, after the functional specification has been made. Main problems in this step are in particular caused by the influence of uncertainty. Uncertainties may, as Braat and Lierop (1987) state, be due to (i) stochastic properties of the system components, (ii) lack of knowledge, i.e. about system state and processes, (iii) problems of data measurement and interpretation, (iv) lack of control on various input factors, (v) limited duration of operationality of control systems and (vi) changing perspectives, moral standards and values. This observation applies also to the subsequent modelling attempts of the above synthesis framework.

4. A Taxonomy of Economic-Ecological Integration

In this section, we will typify different types of models discussed in the relevant literature by identifying different degrees of integration that can be distinguished for economiy-ecology systems. The degree of integration may refer to the above mentioned four essential characteristics of the entire system, viz. objectives, elements, structures and boundaries. We will focus in paricular on the structure of the interacting systems, as the systemic structure implicitly determines the elements and the boundary of the system. Likewise, the objective may be determined by the structure. Consequently, in Subsection 4.1 – 4.3 we will address mainly three structure phenonmena, viz. exogenous constants, a unilateral interaction and integrated modelling.

4.1 Exogenous constants

Economic subsystem

An archetypical economic system might in simple and general economic terms be described by means of Figure 2. In this presentation of the economic system, the boundary of the economic system is clearly defined. Furthermore, the ecological system is viewed as exogenous, so that the economic system is fully independent of the environment. No inputs like natural resources, or outputs like emissions and pollution, are incorporated explicitly.

In this system, the outputs, investments (I) and consumption goods (C), are produced by inputs K (reproducible factors, e.g. capital and/or human capital) and L (non-reproducible factors, e.g. labour);

as well as technologies (A) which in turn are produced by the inputs K and L. This is represented by the production function F(•). Dynamics (or the feedback) in the economic system is obtained by the accumulation function of capital, which is supposed to be determined by the amount of capital available and the reinvestment of production after the consumption; however, the accumulation of capital is reduced by depreciation of physical capital (δ_k). Another type of dynamic involves the case of endogenous technological development, in Figure 2 represented by the possibility of allocating labour to the creation and accumulation of knowledge.

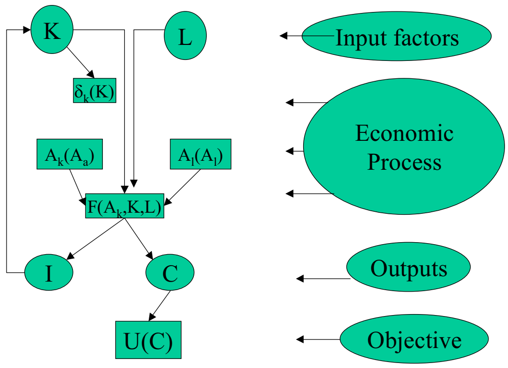

Figure 2: Model of an economic system

The objective of this 'pure' economic system is normally formulated as the maximisation of total social welfare (represented by the function U(•)), which is a function of individual welfare constituents, which in turn are a function of consumption. Given these elements and structure, the free-market and optimum growth rates may be determined in various ways (see Romer 1996). In the Ramsey-Cass-Koopmans formulation, for example, the optimal growth rate is determined by formulating additional assumptions on given initial endowments K and L, as well as assumptions on perfect competition. The balanced growth path in the Solow formulation is derived by the determination of the optimal savings rate, through which the utility from consumption is optimised (see e.g. Romer 1996). Modern variants based on endogenous growth theory provides an explanation for an ever-growing economy by endogenizing the role of investments in technological progress (see e.g. Aghion and Howitt 1998).

Ecological subsystem

The ecological system might in simple general terms be interpreted as a possibly self-regulating system, which may be depicted as follows (see Figure 3). In this system, we have the elements (i) stock of an entity (S) as input; (ii) the regenerative capacity of the system (R(•)) as the mechanisms of the ecological process; and (iii) the flow of an entity (E), e.g., emission of greenhouse gasses or extraction from a stock of fish. The structure of this system is such that both the flow E and the regeneration R(S) affect the stock (S). The simplest way is to model the regenerative capacity as a function of the stock.

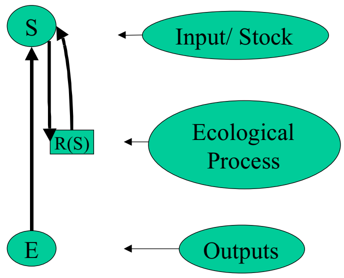

Figure 3: Ecological system

In perceiving the ecological system as a 'living' system and subdividing it into different ecological communities and further specifying it into different populations that are composed of basic elements, namely the individual, we can interpret regenerative capacity in terms of birth and death rates of the population. For example, the birth of the next fish population (R) depends inter alia on the number of the old population fish stock (S). But, the exact dynamic function might be rather cumbersome, if one wishes to incorporate the complexities of real-world systems.

In the literature, an unambiguous formulation of an 'objective' of the ecological system – as postulated by mankind; within an ecosystem, each living species' 'objective' is probably survival – is not easy to find and lies beyond the scope of this paper. Examples of such a meso or macro objective may be biodiversity or sustainability of the ecological system. The dynamics of the ecological system may among others include resilience (Holling 1973, Perrings 1998), biodiversity, compound systems (Clark 1976) or mutualistic systems (Wacker 1999). For a brief overview of other possibilities of including more complexities in ecological systems, we refer to e.g. Gowdy and Carbonell (1999).

The accumulation of the stock (dS(t)/dt) may be formulated as (see e.g. Sweeney 1993, Clark 1976)[2]:

(4.1) $dS(t)/dt = R(S(t)) - E(t)$

Equation 4.1 states that the accumulation of a stock corresponds to the regenerative capacity, i.e. reproduction in case of living systems and recovery in case of natural resources, minus the flow of the entity, i.e. an extraction as a result of unnatural intervention or death. This system may be accompanied by various restrictions, such as:

(4.2a) $S(t) \geq 0$ for all t

to represent a non-negativity constraint, or:

(4.2b) $S(t) \leq S^{max}$ for all t

or

(4.2c) $S(t) \geq S^{min}$ for all t

to represent an upper limit on accumulated emissions (b) or a lower limit on living stocks (c), as specified as policy targets. For literally undepletable resources (e.g. solar energy for the next 5 billion years), the latter type of restriction needs not be made (i.e., the constraint will never be binding).

4.2 Unilateral interactions

Depending on the emphasis in the analysis, the unilateral interaction may be environmental-system oriented or economic-system oriented. In the first case, the ecological system gets an input from the economic system. The model in this type of interaction concerns the changing conditions of the ecological system caused by the economic system. In the second case, an environmental system provides inputs for an economic system.

The focus in the first case is solely on the effect of the economic system on the environmental system in the form of e.g. pollution or extraction, without there being any individual or social planner that attaches a value to this effect. This type of interaction may be illustrated by Figure 4. The boundary of this type of interaction incorporates all individual elements of the separate economic and ecological systems as described in the previous subsection. In this structure however, this type of interaction takes only into account the impact of the economic system on the ecological system.

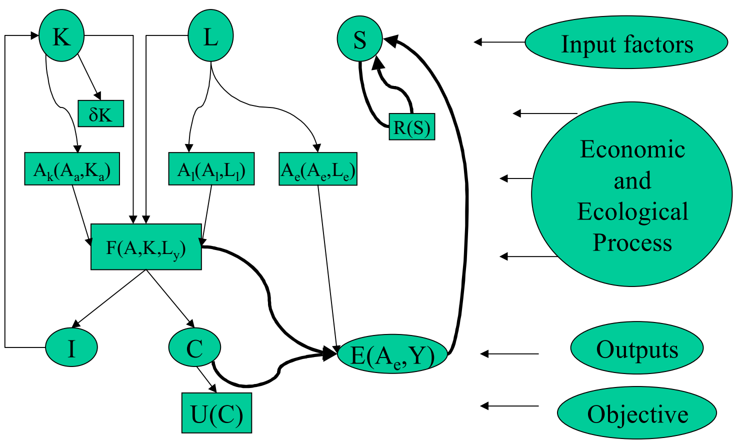

Figure 4: Feedback from the economic system to the environmental system

[2] In case of pollution, the relationship between accumulation of stock on the one hand and the emission and regenerative capacity on the other hand, is the opposite from the natural resource case. Thus, $dS/dt=E(t)-R(S)$.

Applications of this type of modelling would be all studies that only quantify environmental effects of economic activity, without attempting to say anything about the social value of such effects. However, many economic studies (Tahvonen and Kuuluvainen 1991, 1993, Den Butter and Hofkes 1995, and Van Ewijk and Van Wijnbergen 1995) do in fact have a feedback to the economic system via consumption (in the form of waste) or production (in the form of emission or extraction), or utility in general, so that they may essentially be categorised as integrated modelling.

In the second case, the E-E linkage is illustrated in Figure 5 for a macro-economic system.

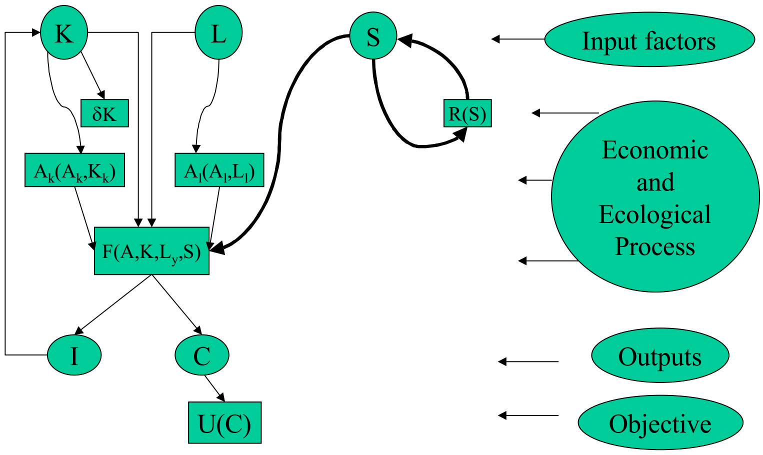

Figure 5: Macro-economic oriented unilateral interaction

In this model, where the main difference with the conventional economic sub-model is formed by the incorporation of environmental amenities in the production function Y=F(K,L,S), there is no feedback to the ecological system for extraction. This model therefore resembles, for example, the situation where the weather influences economic productivity (via the production function), but where the economic subject cannot influence the weather.

4.3. Integrated modelling

The general case of integrated modelling was already presented in Section 3. This type of interaction links the individual elements of both ecological and economic systems and thus also maps out the boundary. However, the structures as well as the purpose of the resulting E-E interacting system, are presented differently in the literature. In other words, the feedback linkages are modelled in various ways, namely via production, consumers' utility, or both. In this section we will consider such integrated models, all of which will be in the category of 'complex integration'.

Integration via production function

The first case, viz. interaction through feedback by production, may be seen as complementary to the resource-oriented model, as the price and cost, which are exogenous in the previous types of model, may then endogenously be determined by this type of model. An example of the literature that focuses on this relationship can be found in Clark (1976). In this case, the objective of the E-E interacting system is the maximisation of the consumers' welfare. This type of interaction may be illustrated by Figure 6.

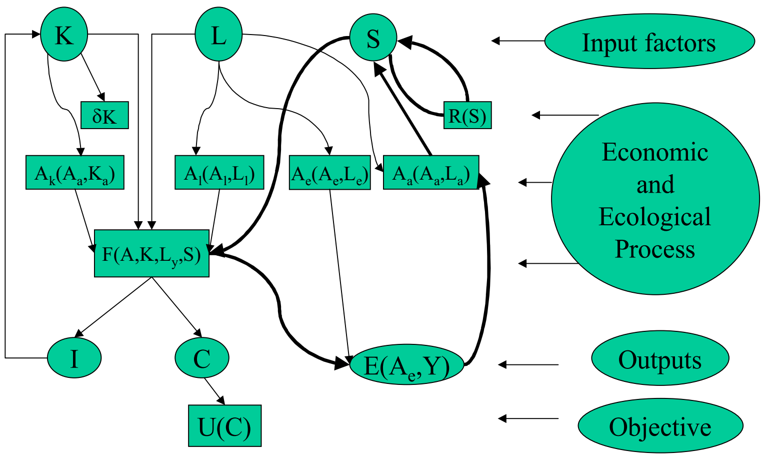

Figure 6: E-E interaction via production

Of course, most ecologically-oriented models are more complex, for example, the climate part of the Dynamic Integrated Climate change and Economy (DICE) model of Nordhaus (1993) already takes relationships between carbon emission and temperature change into account.

A special version of this type of interaction can be found in the natural resource-oriented studies (Hotelling 1931, Beckmann 1974, Clark 1976, Dasgupta and Heal 1974, Stiglitz 1974a, 1974b, Garg and Sweeney 1978), where the optimal rate of extraction or harvesting is investigated on the basis of economic principles. In this literature, the ecological system is brought back into the 'economic' domain (Devarajan and Fisher 1981).

In case of resources, there is the distinction between renewable versus non-renewable as well as depletable versus non-depletable resources. Depletable resources typically correspond to the restriction that: $S(t) \geq 0$ for all t, and S(0) is given (i.e., the total amount of resources). Non-depletable resources are resources that, by approximation, are not restricted, so that a constraint such as (4.2c) will be a slack one. Furthermore, the distinction between renewable and non-renewable resources is that $R(S) \approx 0$ for non-renewable resources (like oil) and $R(S)>0$ for renewable resources (Sweeney 1993). In terms of E-E systems, this type of interaction implies a redefinition of the boundary by including an extra element from the economic system describing the profit from the ecological system ($\pi(\bullet)$), depending on the price of the natural resource (P), the rate of extraction (E) as well as the cost of extraction (Ψ(•)) which in turn depends on the rate of extraction (E) as well as on the amount of the stock available (S). A graphical illustration of these studies is given in Figure 7 and an example of such a model in terms of extraction of natural resources is found in Sweeney (1993).

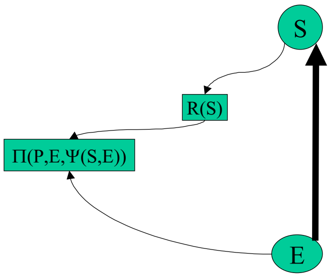

Figure 7: Resource-oriented E-E interaction

The E-E interaction via a production model (see Figure 6) may partly be rewritten in terms of a resource-oriented model, as the profit function (Π(•)) in the resource-oriented model is the outcome of the demand from the economic system (see e.g. Nijkamp 1977). The advantage of writing out the macro-economic sub-model is that in this way, the price for the stock (as a result of the utility function) as well as the costs of extraction (embedded in the production function) are endogenously determined.

Such models are integrated in the sense that profit (or welfare) maximization determines the optimal speed of extraction and hence the development of the stock over time, whereas the stock itself may define the profit or welfare optimizing path of extraction, as well as directly affecting the costs of extraction. Furthermore, such models may be extended by including the factor human knowledge (A) and other kinds of resources (M) in the production function; for example, Y=F(A,K,E,M,S) (see for illustrations e.g. Pezzey 1992, Nijkamp 1977).

Integration via an objective function

The second case, viz. modelling mutual interaction by including environmental factors (E and/or S) in the consumers' utility function, allows for more analytical possibilities for modelling the interaction between both systems. This stream of modelling forms a large part of the literature (see e.g. Thavonen and Kuuluvainen 1991,1993; Byrne 1997, Smulders 1994). The utility function in the context of environmental issues has usually the following general form (see e.g. Aghion and Howitt 1998):

$$\max U(C,S,E)$$

In this formulation, the emission (E) or the stock of pollution (S) are both amenities, because both determine the level of utility. The structure of such E-E interacting system can, depending on the research problem, be presented differently. An example of a graph of this type of feedback in terms of E-E-interaction is given in Figure 8, where regeneration and technological development are omitted for the ease of graphical presentation and where the dashed line means that in some models the stock in ecological systems is not included in the production function.

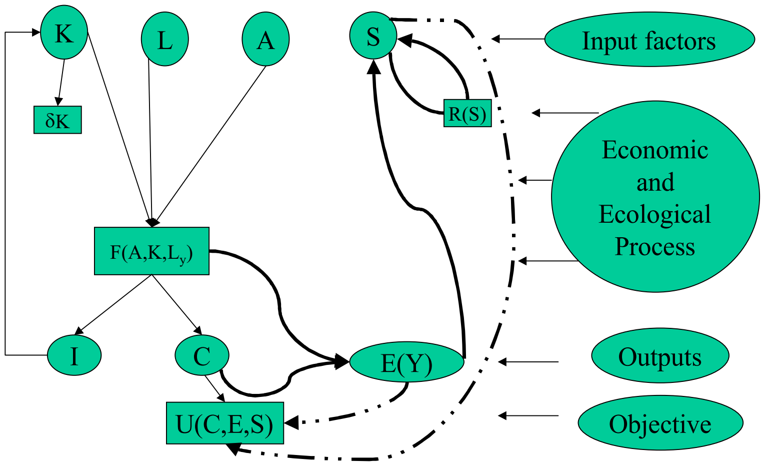

Figure 8: Integrated modelling in terms of consumers' utility

As soon as the presence of E and or S as arguments in the utility function induce behavioural changes due to changes in the ecological sub-system, we have 'complex integration' as outlined above.

As pointed out, the most complete E-E interaction is incorporated in the general model of type Figure 1, as it includes all individual elements, structures, boundaries as well as the drivers of the systems as discussed in the previous subsections. In Figure 1, interaction is achieved by both consumers' utility as well as by the production function. An example of this case is that pollution emission may both affect consumers' utility as well as the production because of e.g. health implications. This model is however rather complicated, as the emission (or stock of resources) in this case influences the consumers' utility in two ways, viz. directly via the utility function and indirectly via the production and thus the consumption. Therefore, it might be difficult to separate the production or consumers' effect in empirical modelling. Note also that when the consumption flows back to the ecological system (via the dashed line by C and E), this system corresponds to a material balance model (see e.g. Van den Bergh 1991), as this is a closed system of material flows. Otherwise, the materials (like waste) remain within the economic system.

5. Spatial Externalities

All economic activities and all ecological phenomena can be mapped out in space. Consequently, all E-E interactions have by definition a spatial component. Our previous framework was based on the assumption that economic variables could be projected in the same geographical space where the ecological variables were located. However, in reality often the economic space and the ecological space do not coincide for mainly two reasons: (i) the source of pollution or the place of reception (ambient concentration) may be mobile; (ii) the pollutant itself may be mobile (e.g., dispersion of air pollution). In such cases, the E-E framework is still valid, but needs a spatial adjustment. This was clearly emphasised in the debate on the ecological footprint (see Wackernagel 1999b), where the missing geographical components of E-E interactions played a key role. From a geographical mapping perspective, the use of GIS in relation to spatial E-E analysis may then be extremely useful, as this allows for a use of different scale levels depending on the phenomenon at hand (see for illustrative example Giaoutzi and Nijkamp 1995).

In this section we will address in particular the formal incorporation of space in the E-E interaction framework. Every element in Figure 1 may be assigned to a region, so that the interacting system becomes rather complicated. Consider for simplicity an interacting system with only 2 regions A and B, each having an economic and an ecological system. Verhoef and Nijkamp (2000), for instance, considered such a setting, and studied the following set of interactions:

1. *Economic A* <--> *Economic B* This involves the market interactions between the two regions, as arising from specialisation and trade. Although market failures could be present in this type of interaction (e.g. due to market power), there is no *a priori* reason to postulate that this be the case (unless the theory of local market power due to transport costs is applied rigorously). Government failures however, may easily be present, in particular if the one government, via trade policies, tries to ‘exploit’ the other region, and/or ignores the impact of environmental splii-overs (see ad 3 below).
2. *Economic A(B)* <--> *Ecological A(B)* This involves the local valuation of local emissions, similar to the expositions given above.
3. *Economic A(B)* <--> *Ecological B(A)* This involves environmental spill-overs: production in the one region leads to environmental degradation in the other. Typically, under non-cooperation, such externalities will not be optimized (from a global perspective) by local governments, as exemplified, for instance, by the location of nuclear power plants near national borders.

In their article, Verhoef and Nijkamp studied first-best and second-best regulations, which turned out to be a highly complicated mixture of trading off various welfare components (local environmental quality, global environmental quality as valued by local residents, terms of trade effects). One could, however, on the basis of the foregoing exposition, envisage an even wider set of interactions in the simple spatial configuration just outlined:

4. *Ecological A* <--> *Ecological B* Ecological phenomena seldom respect political borders. It may often be the case that eco-systems transcend such borders, in which case there is a direct interaction between eco-systems politically assigned to different jurisdictions.
5. *Knowledge A* <--> *Knowledge B* Trade and direct communication may lead to the existence of knowledge spillovers. Insofar as the non-spatial setting shown in Figure 2.1 is subject to endogenous technological development, yet another type of spatial complication is added.
6. *Production factors A* <--> *Production factors B* Certainly capital, but in the longer run also labour has become increasingly mobile between countries and regions. Again, this adds a next important type of spatial interaction to our framework.

It is evident that the number of potential interactions in the overall system increases rapidly (exponentially) with the number of regions considered, and the number of interacting elements (as listed in points 1-6 above) within and between regions. Especially when employing a dynamic (long-run) perspective, as – arguably – appropriate for the study of sustainable development, one has to be prepared to accept that for the study of the implied complex system – in which space and time are added to the elements shown in Figure 1 – analytical techniques will be of limited help. That is, most analytical dynamic optimization problems will yield manageable closed-form solutions, if the number of state variables is in the order of 2 or 3 at a maximum – which clearly is not the case in the framework presented above. The best one can hope for, at least in the short run, would be the use of numerical simulation techniques.

As a corollary, also the formulation of actual policies will be an extremely difficult task, as only little is known about the time-space interactions between all elements that may play a role, and even if the complete mechanism of a time-space expanded version of Figure 2.1 would be known for realistic systems, the derivation of 'optimal' policies would be an extremely difficult task in light of the above considerations. This is exactly why pragmatic concepts such as 'ecological footprints' (Wackernagel, 1999b), although debatable on theoretical grounds (*e.g.* Van den Bergh and Verbruggen, 1999), nevertheless seem attractive to policy makers, and – indeed – may sometimes give valuable or at least quantifiable operational indicators for the sustainability of current developments and the desirability of corrective policies.

6. Conclusion

In this paper, we have provided an analysis framework that categorises the existing literature on the interaction between the ecological and the economic system. As this framework is set up as a basis for a methodological synthesis of ecology-economy interactions, it may be also useful for finding viable research trajectories. Clearly, this framework should be further explored and extended in terms of time, space and specification of the system's structure (functional relationships) as well elements (impact parameters for the variables). The novelty of our contribution is that, by categorising the existing models into various types of E-E interaction, the differences in insights from ecological and economic perspectives and from various modelling studies may be clarified, so that a more transparent research design may be feasible. Therefore, the process of identifying a common research framework for a multidisciplinary approach may be supported by properly addressing the issues of the drivers, the elements, the structure and the boundary of the system.

This is not to say that once such a system would have been specified, the derivation of optimal policy rules becomes an easy task. Given the dynamic and spatial dimensions that are so relevant for the topics studied here, one could foresee a highly complex mix of (at least) environmental, economic, technology, spatial and trade policies – each of these both at a local, regional, national and global level – that would have to be balanced in a rather delicate fashion in order to achieve sustainable development – however defined – in a socially cost-efficient manner. If interactions between these policies – as well as between their primary target elements in our complex system – would be simply ignored, however, the eventual effects of policies may diverge widely from the goals envisaged, and government failures would easily occur. It, therefore, seems safe to conclude that a careful design of policies for a sustainable development, be it based on ecological or economic principles and motivations, cannot do without the acceptance of the methodological challenges offered by complex non-linear dynamic systems modelling.

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